PAPER • OPEN ACCESS

Simulation of infrared photonic crystal fibers based on crystals system $AgBr - TlBr_{0.46}I_{0.54}$

To cite this article: D. D. Salimgareev *et al* 2019 *J. Phys.: Conf. Ser.* **1410** 012145

Simulation of infrared photonic crystal fibers based on crystals system AgBr – $TlBr_{0.46}I_{0.54}$

D. D. Salimgareev, A. A. Lashova, A. S. Shmygalev, A. E. Lvov, L. V. Zhukova
Ural Federal University named after the first President of Russia B.N. Yeltsin. Yekaterinburg, 620002, Russia.

Abstract. In this paper, a computer simulation of photonic crystal fibers (PCF) based on the AgBr – $TlBr_{0.46}I_{0.54}$ system was performed. The simulation was carried out in the SMTP program integrated into Matlab. As a simulation result, PCF with the hexagonal structure of PBG-inserts with an increased mode field diameter of up to 200 µm was obtained.

1. Introduction

Among the infrared materials suitable for the manufacture of optical fibers, monocrystals of silver halides and monovalent thallium are distinguished. One of such monocrystalline system is AgBr - $TlBr_{0.46}I_{0.54}$ crystals, on the basis of which using extrusion infrared fibers can be made that have unique optical properties: a wide transmission range from 2.0 to 25.0 µm, photo- and radiation resistance, small optical loss up to 0.5 dB/m. These properties of IR fibers based on AgBr - $TlBr_{0.46}I_{0.54}$ system crystals make them promising for use in various optical systems [1]. However, various applications require single-mode operation from optical fibers, as well as the transmission of high-power radiation with an increased mode field diameter. To solve these problems, photonic crystal fibers (PCF) of various types are used, in particular PCF with an active core (AC) and surrounding inclusions - photonic bandgaps (PBG) of optically less dense material than the main fiber material - matrix, and the central insert - AC from a more dense substance [2]. PCF AC allow transmitting high-power radiation in a single-mode with a Gaussian distribution of the mode field over the fiber section.

The manufacture of such PCFs is a long and resource-intensive process, which is carried out using a combination of “stack and drow” and “row in tube” technologies, which make it possible to obtain a clear interface and a strict structure of inserts in the fiber. In order to optimize the PCF production process, a computer simulation stage was introduced, necessary for determining the geometric parameters of the fiber and predicting its optical properties.

So computer modeling is used to preliminary determination the mode of operation of the PCF and determine the optimal geometrical parameters, the chemical composition of the matrix and inserts, and the nonlinear optical properties.

2. Materials and methods

Earlier, the authors of [3] developed photo- and radiation resistant, non-hygroscopic, plastic crystals of the AgBr-$TlBr_{0.46}I_{0.54}$ system, which don't have the effect of cleavage, from which optical products (windows, lenses) can be made by hot pressing and optical fibers for the mid-IR range are produced by extrusion. The phase diagram of the AgBr-$TlBr_{0.46}I_{0.54}$ system [3] was studied, based on which single-crystals of various compositions were grown (Fig. 1). It is established that, depending on the composition, the obtained crystals are transparent from 0.46 to 50.0 μm without absorption windows [3, 4], their refractive index varies from 2.165 to 2.389 at wavelengths from 3.0 to 14.0 μm [3 , 4], and also they possess high photo- [5] and radiation resistance [3]. Optical wares (IR fibers, windows, lenses, etc.) made of AgBr-$TlBr_{0.46}I_{0.54}$ crystals system are necessary to create fiber lasers and amplifiers, fiber-optic systems for IR spectroscopy, including in conditions of increased background radiation, low-temperature IR pyrometry, for the transfer of CO (5.3 - 6.2 μm) and CO_2 lasers (9.2 - 10.6 μm) and other applications.

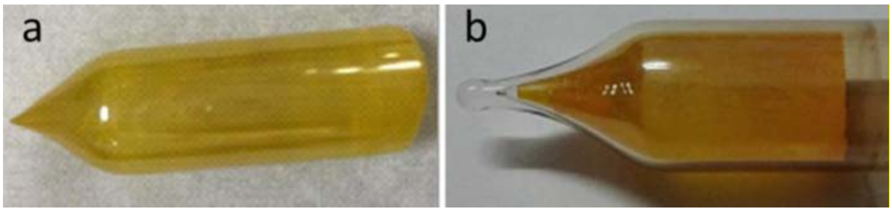

Figure 1. AgBr-$TlBr_{0.46}I_{0.54}$ system single-crystals grown by the Bridgman method: a - 3 mol. % $TlBr_{0.46}I_{0.54}$ in AgBr; b - 10 mol. % $TlBr_{0.46}I_{0.54}$ in AgBr

The fibers were modeled using the SMTP (Source Model Technique Package) software package developed by the authors [6]. This program allows to determine the number of modes passing through the fiber with high convergence of simulation results with experimental data at low computing power costs. The input data for the simulation are the geometry of the PCF, the dielectric and magnetic permeabilities of the media, the refractive indices and the wavelengths of the transmitted radiation. As a result of the simulation, the modes of transmitted radiation, their power, effective refractive indices and the distribution of electromagnetic radiation in the fiber cross section were obtained. When converting two-dimensional pictures into three-dimensional ones, the profile of the radiation distribution over the cross-section of the PCF was evaluated.

3. Experimental data

When simulating PCF based on AgBr-$TlBr_{0.46}I_{0.54}$ (KRS-5) system crystals, KRS-5 contents in silver bromide were taken from 3 to 29 wt.% and the compositions were selected so, that the matrix refractive index was greater than the PBG index, but less than the central insert index. The simulation was performed for a wavelength of λ = 10.6 μm, corresponding to the CO_2-laser emission, with a hexagonal arrangement of the photon inserts and with a central inclusion in the structure core. The fiber core was assumed to be 200 μm, the insert diameters d = 16 μm, the inter-insertion distance Λ = 100 μm. The outer diameter of the fiber was taken equal to 240 μm. In the simulation, the calculation error was set to no more than 10^{-3}, and also the calculation of both the real and imaginary parts of the effective refractive index was specified. The magnitude of the imaginary component of the refractive index was at a value of not less than 10^{-5}, since smaller values do not lead to substantial losses on mode hold.

As a result of the simulation, two-dimensional PCF models were obtained, as well as their effective refractive indices. For all the models obtained, only the valid parts of the index were calculated, which indicates insignificant loss on hold. In addition, photonic fibers with an increased mode field diameter were obtained for each composition. Thus, Figure 1 shows the obtained PCF models with a mode field diameter of up to 200 μm, operating in the single-mode, with the KRS-5 content in AgBr, presented in Table 1.

Table 1. Simulated infrared fiber compositions: KRS-5 content in AgBr in wt.%

№ PCF	PBG inserts	Matrix	Central insert	Effective refractive indices
1	5	10	21	2,192
2	10	21	29	2,203

For each of the selected compositions, single-mode modes of operation were obtained, but to estimate the intensity distribution over the cross section, these models were required to be converted into three-dimensional images (Fig. 2, 3). The obtained three-dimensional structures have a Gaussian radiation distribution in the cross section (Fig. 4) with a high transmittance of power in a continuous mode up to 30 kV / m^2.

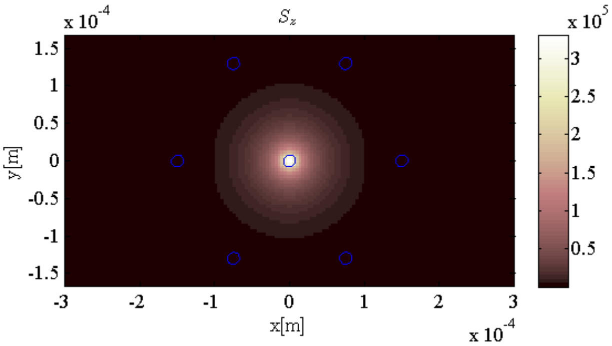

Figure 2. Simulation results of the radiation distribution in the PCF cross section for composition №1 with effective refractive index $n_{eff} = 2.1919$

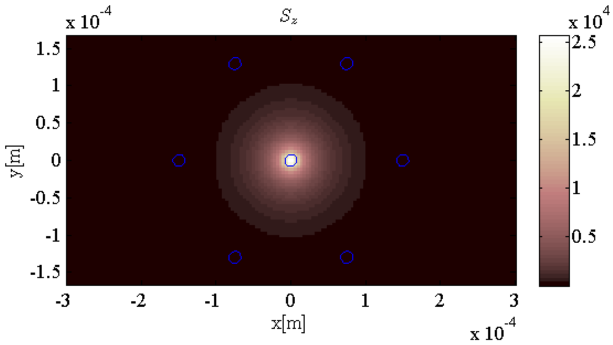

Figure 3. Simulation results of the radiation distribution in the PCF cross section for composition №2 with effective refractive index $n_{eff} = 2.2025$

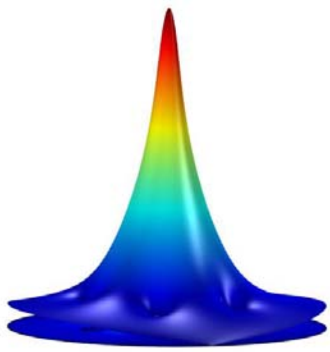

Figure 4. 3-D visualization of the radiation distribution in the PCF cross section with the composition (KRS-5 in AgBr): PBG inserts - 5 wt.%, Matrix - 10 wt.%, Central insert - 21 wt.%

Thus, on the basis of AgBr-$TlBr_{0.46}I_{0.54}$ monocrystals, photonic crystal fibers can be developed for the mid-infrared range of the spectrum, operating in single-mode with an increased mode field diameter. Modeling in the software package SMTP, integrated into the Matlab, confirmed the performance of these fibers.

4. Conclusion

Based on AgBr-$TlBr_{0.46}I_{0.54}$ system crystals, unique photonic-crystal fibers can be developed, transmitting infrared radiation from 2 to 25 µm without absorption windows with low optical losses of no more than 0.5 dB/m and a mode field diameter increased to 200 µm. The manufacture of such fibers is carried out according to the technology of stack-and-drow, which is complex and resource-intensive, and therefore computer simulation is introduced into the PCF production process, which makes it possible to carry out a preliminary assessment of the optical properties and geometrical characteristics of the future fiber. The simulation was carried out in the SMTP software package integrated into Matlab, which allows determining the transmitted radiation modes number, their intensity and effective refractive indices for various fiber configurations. Thus, the simulation allows you to effectively design a PCF structure with the required optical and geometric properties without additional material and time costs. As a result of the simulation, photonic-crystal fibers of two compositions were obtained, each of which provided a single-mode mode of operation at a wavelength of 10.6 µm and a Gaussian radiation distribution over the entire fiber cross section at a maximum radiation power of 30 kW / m^2.

Acknowledgments
This work was supported by the Russian Science Foundation under grant No. 18-73-10063

References

[1] Zhukova L, Korsakov A and Salimgareev D 2015 *Infrared crystals: theory and practice* (Ekaterinburg: Ural federal university) p 215
[2] Broeng D 1999 *Opt. Fiber Technol*. **5** 305
[3] Zhukova L, Lvov A, Korsakov A, Salimgareev D, Korsakov V 2018 *Optics and Spectroscopy* **125** 933
[4] Korsakov A, Salimgareev D, Lvov A, Zhukova L 2017 *Optics and Laser Technology* **93** 18
[5] Korsakov A, Salimgareev D, Lvov A, Zhukova L 2016 *Optical Materials* **62** 534
[6] Hochman A, Leviatan Y 2004 *J. Opt. Soc. Am. A*. **21-6.** 1073